LETHALITY OF UNPROTECTED PERSONS DUE TO DEBRIS AND FRAGMENTS

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ABSTRACT

A quantitative model for the prediction of the lethality of unprotected persons due to debris and fragments is presented. The model provides the basis for the quantitative assessment of hazards caused by debris and fragments from various sources such as crater ejecta, building debris and fragments from bombs and shells.

In a first step, the effects of a single piece of debris onto exposed persons are investigated. The lethalities of different body regions are evaluated in terms of the debris characteristics.

In a second step, the lethality caused by the whole debris shower is obtained by superposition.

A sample application shows how the model can be used to predict the lethality caused by crater ejecta from surface explosions on soil.

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INTRODUCTION

In Switzerland, the safety of manufacturing and storage of ammunition and explosives has, for some time, been assessed by means of a quantitative risk analysis. In this analysis the expected damage in case of a possible explosion is estimated. For this purpose, the effects of an explosion as well as the danger resulting to persons at each location in the surroundings of the potential source of explosion must be known.

In the course of compiling data on explosion effects it was noticed that only few data are available on the effects of debris and fragments. Often, these effects cause the dominating risk for persons in the open. To fill this gap, a comprehensive research programme has been started in Switzerland. This paper summarizes the results of the efforts to develop a *model for the quantitative assessment of the lethality for persons exposed to debris throw.*

In addition, the results of the application of the model to hazards created by crater debris from surface explosions on soil are presented.

STRUCTURE OF THE PROBLEM

The assessment of the lethality of persons caused by debris throw can be divided into the investigation of the debris shower and the investigation of the effects on persons (see page 2).

The *properties of the debris shower* caused by explosions depend on many parameters: type of explosive, casing and confinement of the charge, height of burst, surroundings (e.g. barricades, woods, topography), etc. Therefore, a general treatment is hardly possible.

To serve as an illustration, the results of the investigation about crater debris shower characteristics caused by surface explosions on soil are presented in the example at the end of this paper.

The investigation of the *effects of debris on persons* can be subdivided in the evaluation of the lethalities caused by *single* debris and the determination of

the lethality caused by the whole *debris shower*.

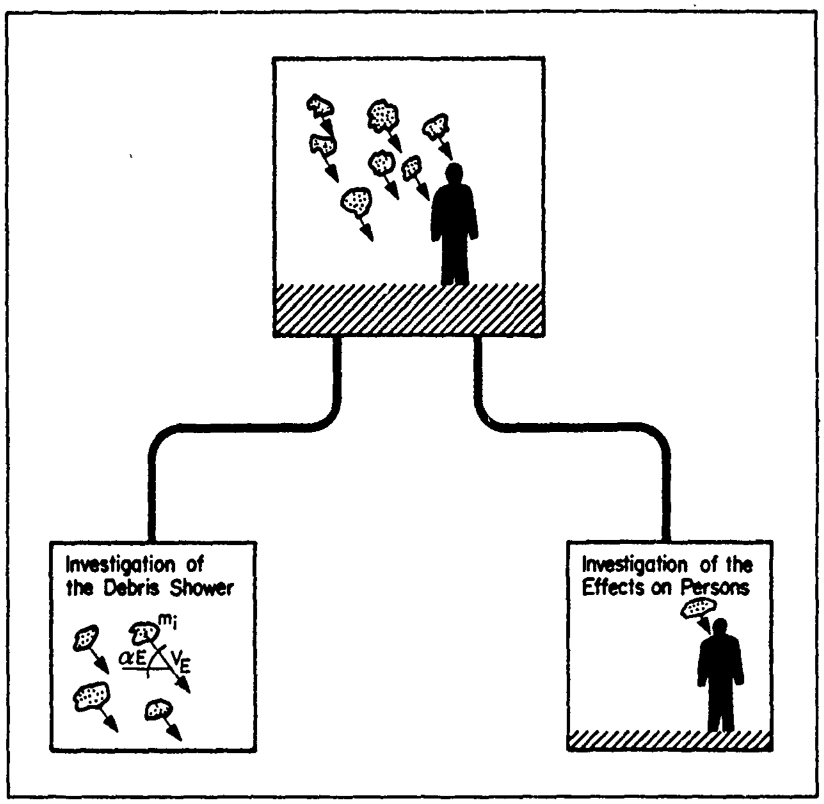

Figure 1: Structure of the problem: Lethality caused by debris throw

INVESTIGATION OF THE LETHALITY CAUSED BY SINGLE DEBRIS

When investigating the lethality of a person due to single impacting debris, its characteristics relevant for the lethality are assumed to be known.

For the determination of the lethality, the following two factors are of importance:

- Location of impact on human body
- Probability of this location being hit by a single piece of debris

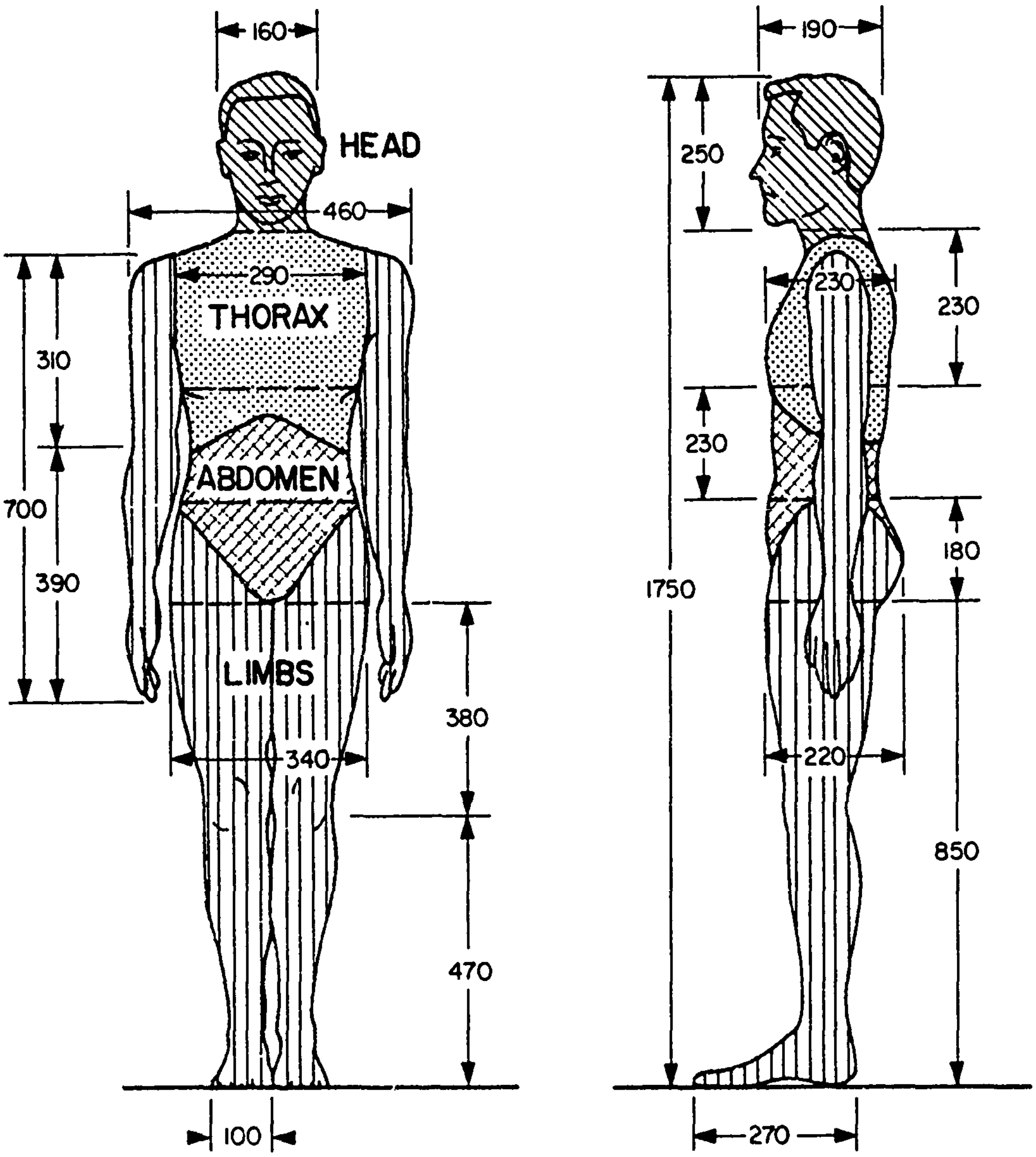

Figure 2: Example for the dividing of the body into regions with similar sensitivity and measurements of the "Standard Man" in mm

Influence of the location of Impact

In our model, the location of an impact is being accounted for by dividing the body into several regions. It is assumed that the sensitivity to debris remains approximately the same at all points within one region.
The body can, of course, be divided into any number of such regions. However, this is sensible only insofar as it is possible to provide quantitative information concerning the different sensitivities.

In the example of Figure 2, the body has been divided into four regions.

For the individual regions, the probability that a single impacting piece of debris would be lethal has to be determined. This probability is called the basic lethality λ^B_{ij} of debris i on region j. These basic lethalities depend on many parameters which concern the characteristics of the debris as well as those of the exposed person itself. Figure 3 shows the most important parameters which influence the basic lethalities:

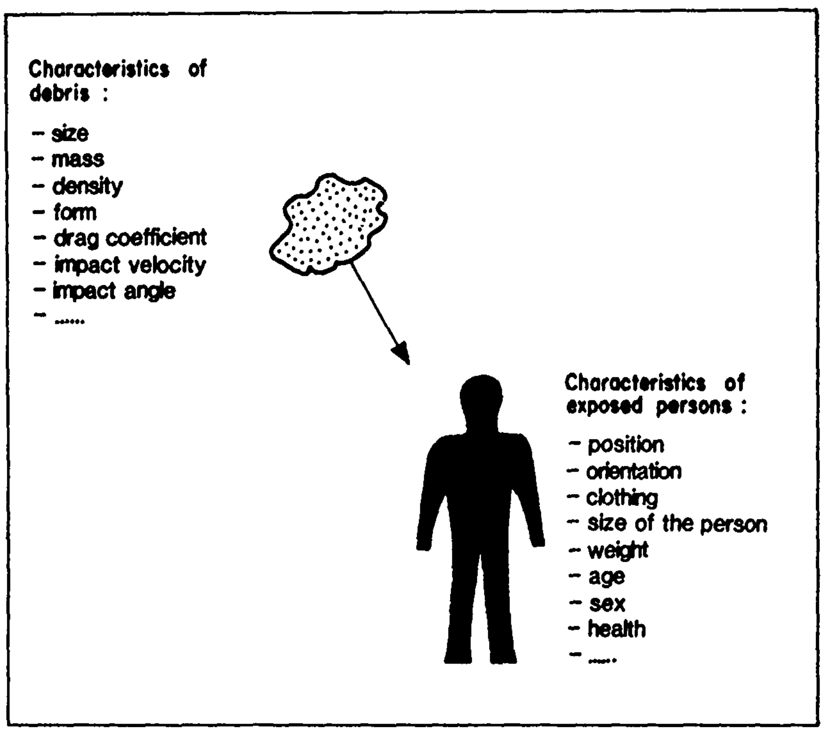

Figure 3: Parameters influencing the basic lethalities

To give an example, basic lethalities caused by impacting, non-penetrating debris (e.g. crater debris) are given in Figure 4. These lethalities were established during the evaluation of various data of the respective literature (Ref. 2 - 9). In the case of non-penetrating debris it is normally assumed that their kinetic energy ($mv^2/2$) is the decisive factor for the lethality.

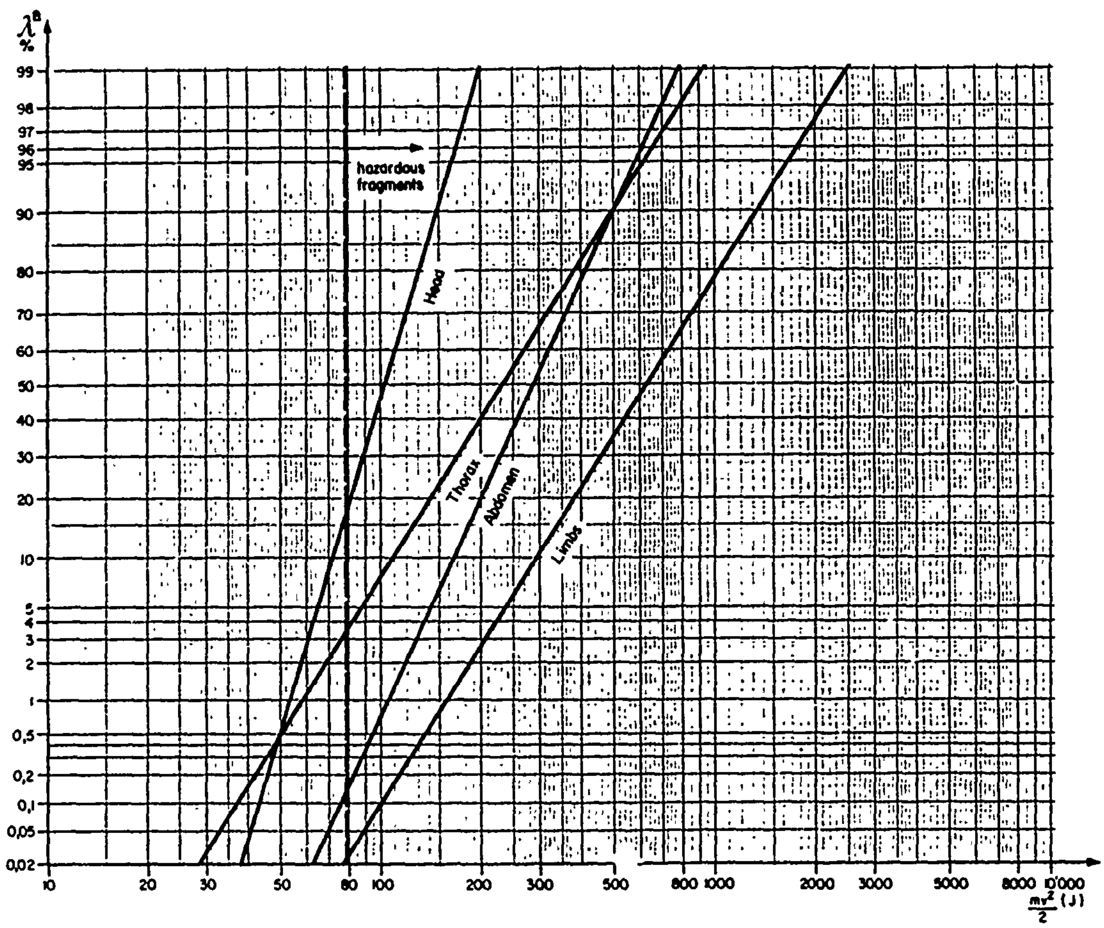

Figure 4: Basic lethalities due to impacting (non-penetrating) debris depending on kinetic energy

In addition, Figure 4 shows the 79-Joule-criterion (= 58 ft · lb) which is also used in the NATO Safety Principles for the storage of ammunition and explosives (Ref. 10). As mentioned in Ref. 11, this very old criterion appears to have been

borrowed initially from the German Army Doctrine (Ref. 12) at the beginning of this century. In its crudest form, this criterion stated that missiles with less than 79 J of kinetic energy do not kill, and that those with more than 79 J do kill.

Figure 4 tells us that this criterion overestimates the effects of non-penetrating debris.

Probability of hitting a given location

For the investigation of the lethalities caused by a single piece of debris, the probability of each region being hit plays an important role. To account for this probability, the projected area Λ_{ij} of the body region j onto the horizontal surface (see Figure 5) is used. These projected areas mainly depend on size, position (standing, lying, sitting) and orientation (front, back, side) of the exposed person. In comparison to this, the NATO Safety Principles assume the projected area of the whole body to be constant ($\Lambda = 0.58\ m^2$).

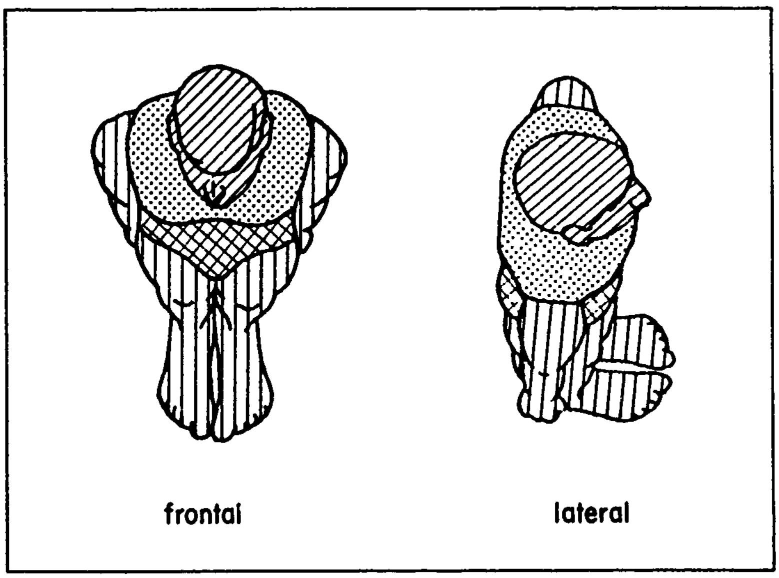

Figure 5: Projected areas of the body regions onto the horizontal surface; Example: impact angle $\alpha_E = 80°$

Lethality caused by single debris

Using the two definitions "Basic Lethality $\lambda^B{}_{ij}$" and "Projected Area Λ_{ij}" the lethality of a single piece of debris hitting the body (anywhere) can be established as follows:

$$\lambda_i = \frac{\sum_{j=1}^{q} \cdot \lambda^B{}_{ij} \cdot \Lambda_{ij}}{\sum_{j=1}^{q} \cdot \Lambda_{ij}} \quad (1)$$

Lethality caused by multiple debris

Knowing the lethality λ_i of a single piece of debris hitting a body, the lethality of p impacting debris can be calculated as follows:

$$\lambda = 1 - (1 - \lambda_1)\cdot(1 - \lambda_2)\cdot \ldots \cdot(1 - \lambda_i)\cdot \ldots \cdot(1 - \lambda_p) \quad (2)$$

In practice, however, it is hardly possible to determine the lethality λ_i of every single piece of a debris shower. It is necessary to make simplifications, for instance, by selecting groups of debris with similar characteristics (e.g. similar values for impact velocity and impact angle).

The debris density $\overline{\delta}_i$ is usually evaluated (number of debris per unit area) when tests or hazard evaluations are made. Therefore, this quantity is used in Table 1 to characterize the number of debris in each group. Based on these data, the lethality of n debris groups can be calculated as follows:

$$\lambda = 1 - e^{-\sum_{i=1}^{n} (\overline{\delta}_i \cdot \lambda_i \cdot \sum_{j=1}^{q} \Lambda_{ij})} \quad (3)$$

Table 1: Debris groups

Group	Mass	Impact Velocity	Impact Angle	Mass Density	....	Debris Density	Lethality
1	m_1	v_{E_1}	α_{E_1}	ρ_1		$\bar{\delta}_1$	λ_1
2	m_2	v_{E_2}	α_{E_2}	ρ_2		$\bar{\delta}_2$	λ_2
.							
.							
i	m_i	v_{E_i}	α_{E_i}	ρ_i		$\bar{\delta}_i$	λ_i
.							
.							
n	m_n	v_{E_n}	α_{E_n}	ρ_n		$\bar{\delta}_n$	λ_n

The following equation results when equation (1) and (3) are combined:

$$\lambda = 1 - e^{-\sum_{i=1}^{n} [\bar{\delta}_i \cdot \sum_{j=1}^{q} (\lambda^B{}_{ij} \cdot \Lambda_{ij})]} \tag{4}$$

The literature often uses the debris mass density δ_i (debris mass per unit area) instead of the debris density $\bar{\delta}_i$ (debris of group i per unit area). Both quantities are connected as follows:

$$\bar{\delta}_i = \frac{\Psi_i}{m_i} \cdot \delta \tag{5}$$

$\bar{\delta}_i$ = debris density of debris group i

Ψ_i = percentage of weight of debris group i

m_i = average debris mass of group i

δ = debris mass density = debris mass of all groups per unit area

With relationship (5) formula (3) can be transformed into:

$$\lambda = 1 - e^{-\delta \cdot \sum_{i=1}^{n} [\frac{\Psi_i}{m_i} \cdot \sum_{j=1}^{q} (\lambda^B{}_{ij} \cdot \Lambda_{ij})]} \tag{6}$$

EXAMPLE: LETHALITY DUE TO CRATER EJECTA FROM A SURFACE EXPLOSION ON SOIL

In Ref. 1, the described model has been applied for the evaluation of the lethality of unprotected persons caused by uncased surface explosions on soil. In the following, the results are shown together with the most important assumptions.

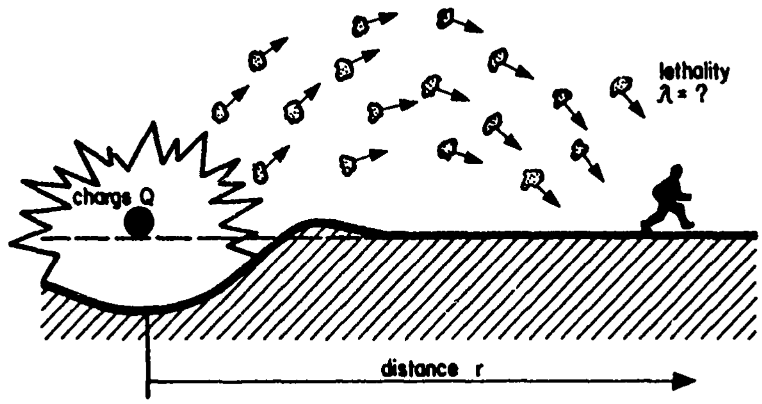

Figure 6: Problem: Lethality due to crater ejecta from a surface explosion on soil

The investigation of the debris shower involves the following three steps:

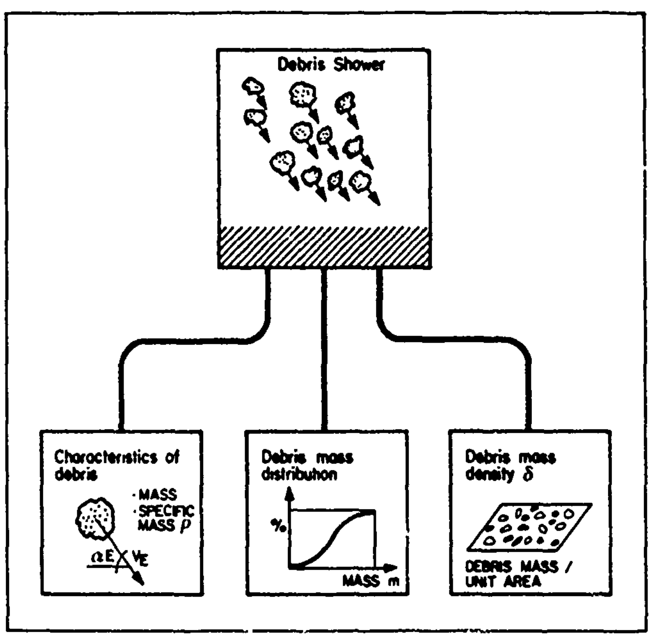

Figure 7: Set-up for the investigation of the debris shower

Based on the evaluation of various data from the literature (Ref. 13 - 20), the following crater ejecta characteristics have been established:

Table 2: Assumptions concerning the specifications of crater ejecta

Properties	Range	Assumption for the Example
Form	spherical to cubical	
Drag. coeff. c_D	$0.47 < c_D < 0.80$	$c_D = 0.64$
Density ρ	$1700\ kg/m^3 < \rho < 2300\ kg/m^3$	$\rho = 2000\ kg/m^3$
Impact Angle α_E	$60° < \alpha_E < 90°$	$\alpha_E = 80°$
Impact Velocity v_E	$v_E < v_{ballistic} \cong 61\ m^{1/6}$ $v_E <$ initial velocity v_o (at horizontal terrain)	$v_E = 61\ m^{1/6}$

The *distribution of the debris mass* depends on the type of ground, in the case of cohesive soil also on the size of the charge. Figure 8 shows examples of typical size distributions.

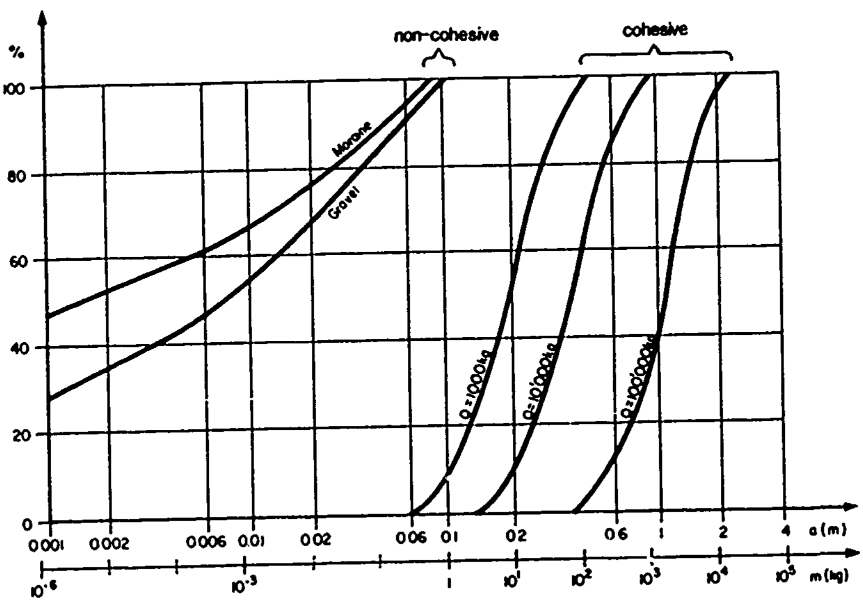

Figure 8: Distribution of debris size and mass on various types of ground and with different charge weights

Upon using this model, it was assumed that the distribution of debris sizes in percent does not depend on the distance from the charge. This simplification is justified for charge weights up to approx. 100'000 kg (see Middle Gust Tests, Ref. 20). In case of bigger charges one can find a disassociation with increasing distances: medium-sized debris fly the farest, whereas extremely small and extremely big fragments show a shorter trajectory.

By comparing numerous relationships found in the literature the *debris mass density* δ (= debris mass per horizontal unit area) was determined to be

$$\delta = 27 \cdot Q^{1.4} \cdot r^{-3.6} \tag{7}$$

δ (kg/m^2), Q (kg), r (m)

The basic lethalities as listed in Figure 4 were used to describe the sensitivity of persons. The impace velocities v_E according to Table 2 had to be adjusted as the velocities vertical to the body surface are decisive for the basic lethalities.

Based on these assumptions, the *lethalities of unprotected persons caused by crater ejecta* can be calculated as follows:

$$\delta = 1 - e^{-27 \cdot Q^{1.4} \cdot r^{-3.6} \cdot \beta} \tag{8}$$

The values for β depend on the position and the orientation of the person, and on the ground material. For standing persons and non-cohesive soil it amounts to $\beta = 0.015$. Figure 9 illustrates the relationship between lethality and distance and the relationships for various charge weights Q.

Figure 9 also illustrates the lethality relationship for a charge weight of 100'000 kg based on the assumptions made on the sensitivity of persons in the NATO Safety Principles (critical energy = 79 joule, exposed area = 0.58 m^2).

This comparison shows that distances may differ by as much as a factor of two.

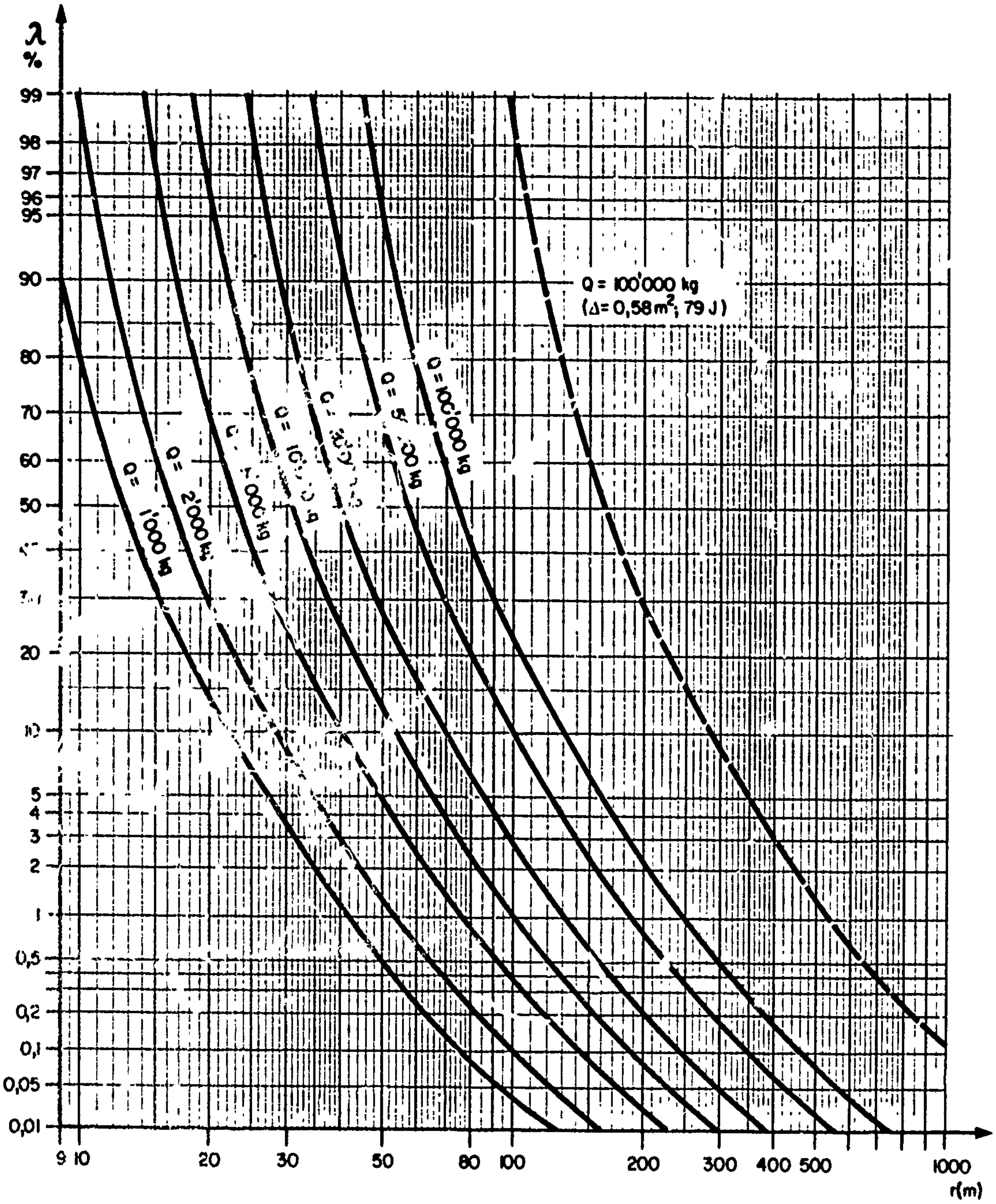

Figure 9: Lethality for standing persons caused by crater ejecta from surface explosions on non-cohesive soil

SUMMARY AND CONCLUSIONS

To allow the practical application of risk analyses, basic information must be available on the dangers to which persons are exposed to by each of the individual explosion effects. In the literature, however, only few data exist with respect to the dangers to which persons are exposed because of debris and fragment throw. Therefore, this problem has been extensively studied in Switzerland. In a first step, a model has been elaborated to determine the effects of various types of debris and fragments.

The advantages of this model can be summarized as follows:

- Differentiating of influencing parameters

  A practically unlimited number of parameters relating to debris characteristics or persons can be considered.

- Systematic Set-up

  By way of systematically structuring the model, the interrelationship between the individual parameters and their influence on the lethality can clearly be shown.

- General Applicability

  The model is put together in such a way that it can be used for all kinds of flying or dropping objects. Besides the presented example of the lethality caused by crater ejecta, the model has also been used for the investigation of debris from donor or acceptor buildings, for fragments of shells or bombs, etc.

  The applicability of this model is limited insofar as part of the required quantitative information is unsufficient up to this day.

REFERENCES

(1) Gruppe für Rüstungsdienste:
"Letalität von ungeschützten Personen infolge Kraterauswurf"
(Lethality of unprotected persons caused by crater ejecta)
P. Janser, Ernst Basler & Partners, Zürich, I 3113-2, December 1981

(2) Sperrazza and Kokinakis:
"Ballistic Limits of Tissue and Clothing"
Annals of the New York Academy of Sciences, Volume 152, Art. I

(3) I. Bowen et al:
"Biological Effects of Blast from Bombs. Glass Fragments as Penetrating Missiles and Some of the Biolobical Implications of Glass Fragmentes by Atomic Explosions"
USAEC Report AECU-3350

(4) S. Butler:
"High-Velocity Fragment Penetration into Sand"
Army Engineer Waterways Experiment Station, Vicksburg, 1976

(5) Feinstein:
"Fragment Hazard Criteria"
13th Explosives Safety Seminar, Defense Documentation Explosives Safety Board, 1974

(6) C.S. White et al:
"The Environmental Medical Aspects of Nuclear Blast"
Technical Progress Report DASA 1341, Lovelace Foundation for Medical Education and Research, Albuquerque, New Mexico, 1962

(7) C.S. White:
"The Scope of Blast and Shock Biology and Problem Areas in Relating Physical and Biological Parameters)
Annals of the New York Academy of Sciences, Volume 152, Art. I

(8) G. Hellström:
"Closed Liver Injury"
A clinical and experimental study, Almqvist & Wiksell, Uppsala, Sweden 1965

(9) C.S. White et al:
"Biological Tolerance to Air Blast and Related Biomedical Criteria"
USAEC Report SEC 65.4

(10) "Manual on NATO Safety Principles for the Storage of Ammunition and Explosives 1976"
Group of Experts on the Safety Aspects of Transportation and Storage of Military Ammunition and Explosives, AC/258 - D/258

(11) David Freud:
"Origin and Subsequent Modifications of Explosives Safety Quantity-Distance (ESQD) Standards for Mass Detonating Explosives with Special Reference to Naval Vessels"
David W. Taylor Naval Ship Research and Development Center, May 78

(12) Rohne H.:
"Schiesslehre für Infanterie", 1906

(13) Gruppe für Rüstungsdienste / Technische Abteilung 6:
"Grösse und Auswurfmasse von Kratern in Lockergestein bei Oberflächen-explosionen"
H. Lüchinger, Basler & Hofmann, B 555.2-50, April 1979

(14) Gruppe für Rüstungsdienste / Technische Abteilung 6:
"Splitter- und Trümmerwirkung auf geschützte und ungeschützte Personen"
P. Janser, Basler & Hofmann, TM 555.2-67, December 1980

(15) H.J. Linnerud:
"Ejecta Sizing for Middle Gust Test Series and a Review of Ejecta Dynamics"
Defense Nuclear Agency, Washington D.C., DNA 4230 F, December 1976

(16) Allen D. Rooke:
"Graphic Portrayal of Discrete Explosion-Produced Crater-Ejecta Characteristics"
Waterways Experiment Station, June 1976

(17) William:
"A Dynamic Crater Ejecta Model"
Science Application, Inc., DNA 001-76-C-0023

(18) Amt für Bundesbauten:
"Modellversuche für oberirdische Explosivstoffmagazine", Teile I bis III
P. Janser, Basler & Hofmann, B 952-4, 1980

(19) Gruppe für Rüstungsdienste / Technische Abteilung 6:
"Wissenschaftlich-technische Grundlagen für die Berechnung von Schaden-wirkungen durch Explosionen"
P. Janser, A. Bienz, P. Kummer, E. Basler & Partners, TM 727-11, 1981

(20) Allen D. Rooke:
"Crater-Ejecta Hazard Predictions in Cohesive Soils, The Middle Gust I Event"
Mississippi State University, August 1980

(21) Gruppe für Rüstungsdienste / Technische Abteilung 6:
"Splitter- und Trümmerwirkung auf geschützte und ungeschützte Personen"
P. Janser, Basler & Hofmann, TM 555.2-67, December 1980